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Solar energy: Markets, economics and policies

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ABSTRACT

Solar energy has experienced phenomenal growth in recent years due to both technological improvements resulting in cost reductions and government policies supportive of renewable energy development and utilization. This study analyzes the technical, economic and policy aspects of solar energy development and deployment. While the cost of solar energy has declined rapidly in the recent past, it still remains much higher than the cost of conventional energy technologies. Like other renewable energy technologies, solar energy benefits from fiscal and regulatory incentives, including tax credits and exemptions, feed-in-tariff, preferential interest rates, renewable portfolio standards and voluntary green power programs in many countries. The emerging carbon credit markets are expected to provide additional incentives to solar energy deployment; however, the scale of incentives provided by the existing carbon market instruments, such as, the Clean Development Mechanism of the Kyoto Protocol is limited. Despite the huge technical potential, the development and large scale deployment of solar energy technologies world-wide still has to overcome a number of technical, financial, regulatory and institutional barriers. The continuation of policy supports might be necessary for several decades to maintain and enhance the growth of solar energy in both developed and developing countries.

Contents

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1. Introduction

Solar energy technologies have a long history. Between 1860 and the First World War, a range of technologies were developed to generate steam, by capturing the sun's heat, to run engines and irrigation pumps [1]. Solar photovoltaic (PV) cells were invented at Bell Labs in the United States in 1954, and they have been used in space satellites for electricity generation since the late 1950s [2]. The years immediately following the oil-shock in the seventies saw much interest in the development and commercialization of solar energy technologies. However, this incipient solar energy industry of the 1970s and early 80s collapsed due to the sharp decline in oil prices and a lack of sustained policy support [3]. Solar energy markets have regained momentum since early 2000, exhibiting phenomenal growth recently. The total installed capacity of solar based electricity generation capacity has increased to more than 40 GW by the end of 2010 from almost negligible capacity in the early nineties [4].

Solar energy has also experienced an impressive technological shift. While early solar technologies consisted of small-scale photovoltaic (PV) cells, recent technologies are represented by solar concentrated power (CSP) and also by large-scale PV systems that feed into electricity grids. The costs of solar energy technologies have dropped substantially over the last 30 years. For example, the cost of high power band solar modules has decreased from about $27,000/kW in 1982 to about $4000/kW in 2006; the installed cost of a PV system declined from $16,000/kW in 1992 to around $6000/kW in 2008 [5,6,7]. The rapid expansion of the solar energy market can be attributed to a number of supportive policy instruments, the increased volatility of fossil fuel prices and the environmental externalities of fossil fuels, particularly greenhouse gas (GHG) emissions.

Technically, solar energy has resource potential that far exceeds the entire global energy demand [8,9]. Despite this technical potential and the recent exponential growth of the market, the contribution of solar energy to the global energy supply mix is still negligible [10]. One may wonder why the role of solar energy in meeting the global energy supply mix is so a small. What are the key barriers that prevented large-scale deployment of solar energy in the national energy systems? What types of policy instruments have been introduced to boost the solar energy markets? Have these policies produced desired results? If not, what type of new policy instruments would be needed? This study attempts to answer some of these questions. Moreover, a large body of literature addressing the engineering dimensions of solar energy is available; yet, literature dealing with economics and policies is limited. This study is also expected to contribute to filling this gap.

A number of studies, including Arvizu et al. [11], have addressed various issues related to solar energy. This study presents a synthesis review of existing literature as well as presents economic analysis to examine competitiveness solar energy with fossil energy counterparts. Our study shows that despite a large drop in capital costs and an increase in fossil fuel prices, solar energy technologies are not yet competitive with conventional technologies for electricity production. The economic competitiveness of these technologies does not improve much even when the environmental externalities of fossil fuels are taken into consideration. Besides the economic disadvantage, solar energy technologies face a number of technological, financial and institutional barriers that further constrain their large-scale deployment. Policy instruments introduced to address these barriers include feed in tariffs (FIT), tax credits, capital subsidies and grants, renewable energy portfolio standards (RPS) with specified standards for solar energy, public investments and other financial incentives. While FIT played an instrumental role in Germany and Spain, a mix of policy portfolios that includes federal tax credits, subsidies and rebates, RPS, net metering and renewable energy certificates (REC) facilitated solar energy market growth in the United States. Although the clean development mechanism (CDM) of the Kyoto Protocol has helped the implementation of some solar energy projects, its role in promoting solar energy is very small as compared to that for other renewable energy technologies because of cost competitiveness. Existing studies we reviewed indicate that the share of solar energy in global energy supply mix could exceed 10% by 2050.

The paper is organized as follows: Section 2 presents the current status of solar energy technologies, resource potential and market development. This is followed by economic analysis of solar energy technologies, including sensitivities on capital cost reductions and environmental benefits. Section 4 identifies the technical, economic, and institutional barriers to the development and utilization of solar energy technologies, followed by a review of existing fiscal and regulatory policy approaches to support solar energy development in Section 5. The role of efforts to combat climate change on the deployment of solar energy technologies is highlighted in Section 6. Section 7 briefly portrays the future prospects for solar energy. Finally, key conclusions are drawn in Section 8.

2. Current status of solar energy technologies and markets

2.1. Technologies and resources

Solar energy refers to sources of energy that can be directly attributed to the light of the sun or the heat that sunlight generates [1]. Solar energy technologies can be classified along the following *continuum*: (1) passive and active; (2) thermal and photovoltaic; and (3) concentrating and non-concentrating. Passive solar energy technology merely collects the energy without converting the heat or light into other forms. It includes, for example, maximizing the use of day light or heat through building design [3,12]. In contrast, active solar energy technology refers to the harnessing of solar energy to store it or convert it for other applications and can be broadly classified into two groups: (i) photovoltaic (PV) and (ii) solar thermal. The PV technology converts radiant energy contained in light quanta into electrical energy when light falls upon a semiconductor material, causing electron excitation and strongly enhancing conductivity [13]. Two types of PV technology are currently available in the market: (a) crystalline silicon-based PV cells and (b) thin film technologies made out of a range of different semi-conductor materials, including amorphous silicon,

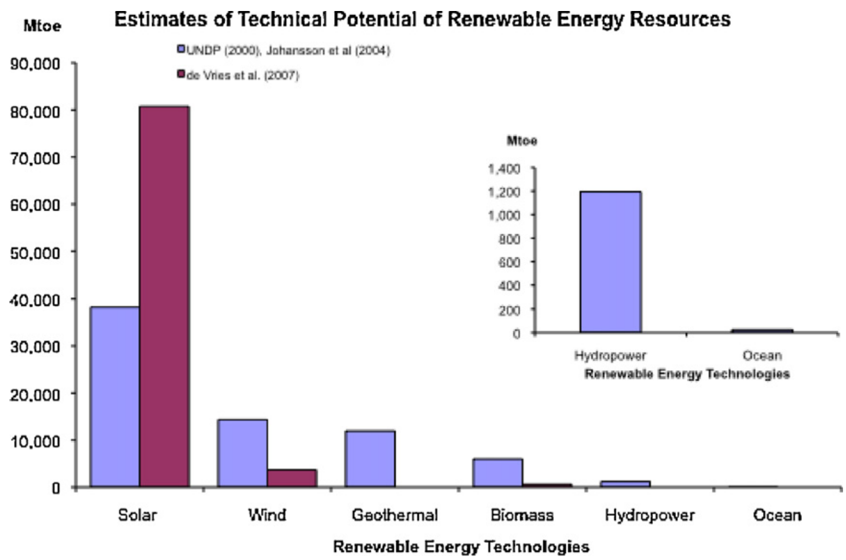


Fig. 1. Technical potential of renewable energy technologies.
Data source: UNDP [109], Johansson et al. [110] and de Vries et al. [18].

cadmium–telluride and copper indium gallium diselenide.[1] Solar thermal technology uses solar heat, which can be used directly for either thermal or heating application or electricity generation. Accordingly, it can be divided into two categories: (i) solar thermal non-electric and (ii) solar thermal electric. The former includes applications as agricultural drying, solar water heaters, solar air heaters, solar cooling systems and solar cookers[2] (e.g. [14]); the latter refers to use of solar heat to produce steam for electricity generation, also known as concentrated solar power (CSP). Four types of CSP technologies are currently available in the market: Parabolic Trough, Fresnel Mirror, Power Tower and Solar Dish Collector [15–17].

Solar energy represents our largest source of renewable energy supply. Effective solar irradiance reaching the earth's surface ranges from about 0.06 kW/m^2 at the highest latitudes to 0.25 kW/m^2 at low latitudes. Fig. 1 compares the technically feasible potential of different renewable energy options using the present conversion efficiencies of available technologies. Even when evaluated on a regional basis, the technical potential of solar energy in most regions of the world is many times greater than current total primary energy consumption in those regions [18].

Table 1 presents regional distribution of annual solar energy potential along with total primary energy demand and total electricity demand in year 2007. As illustrated in the table, solar energy supply is significantly greater than demand at the regional as well as global level.

Kurokawa et al. [9] estimate that PV cells installed on 4% of the surface area of the world's deserts would produce enough electricity to meet the world's current energy consumption. Similarly, EPIA [8] estimates that just 0.71% of the European land mass, covered with current PV modules, will meet the continent's entire electricity consumption. In many regions of the world 1 km^2 of land is enough to generate more than 125 gigawatt hours (GWh) of electricity per year through CSP technology.[3] In China, for example, 1% (26,300 km^2) of its "wasteland" located in the northern and western regions, where solar radiation is among the highest in the country, can generate electricity equivalent to 1300 GW – about double the country's total generation capacity projected for year 2020 [19]. In the United States, an area of 23,418 km^2 in the sunnier southwestern part of the country can match the present generating capacity of 1067 GW [20].

2.2. Current market status

The installation of solar energy technologies has grown exponentially at the global level over the last decade. For example, as illustrated in Fig. 2(a), global installed capacity PV (both grid and off-grid) increased from 1.4 GW in 2000 to approximately 40 GW in 2010 with an average annual growth rate of around 49% [4]. Similarly, the installed capacity of CSP more than doubled over the last decade to reach 1095 MW by the end of 2010. Non-electric solar thermal technology increased almost 5 times from 40 GW_{th} in 2000 to 185 GW_{th} in 2010 (see Fig. 3). The impetus behind the recent growth of solar technologies is attributed to sustained policy support in countries such as Germany, Italy United States, Japan and China.

2.2.1. Solar PV

By December 2010, global installed capacity for PV had reached around 40 GW[4] of which 85% grid connected and remaining 15% off-grid [4]. This market is currently dominated by crystalline silicon-based PV cells, which accounted for more than 80% of the market in 2010. The remainder of the market almost entirely consists of thin film technologies that use cells made by directly depositing a photovoltaic layer on a supporting substrate.

As illustrated in Fig. 2b, a handful of countries dominate the market for PV. However, a number of countries are experiencing a significant market growth. Notably, Czech Republic had installed nearly 2 GW of solar PV by December 2010 [4], up from almost zero

[1] While thin film technologies are less efficient than silicon based cells, they are cheaper and more versatile than crystalline silicon based counterparts.

[2] Suitable sites for installing solar thermal collectors should receive at least 2000 kWh of sunlight radiation per square meter annually and are located within less than 40 degrees of latitude North or South. The most promising areas include the South-Western United States, Central and South America, North and Southern Africa, the Mediterranean countries of Europe, the Near and Middle East, Iran and the desert plains of India, Pakistan, the former Soviet Union, China and Australia [25].

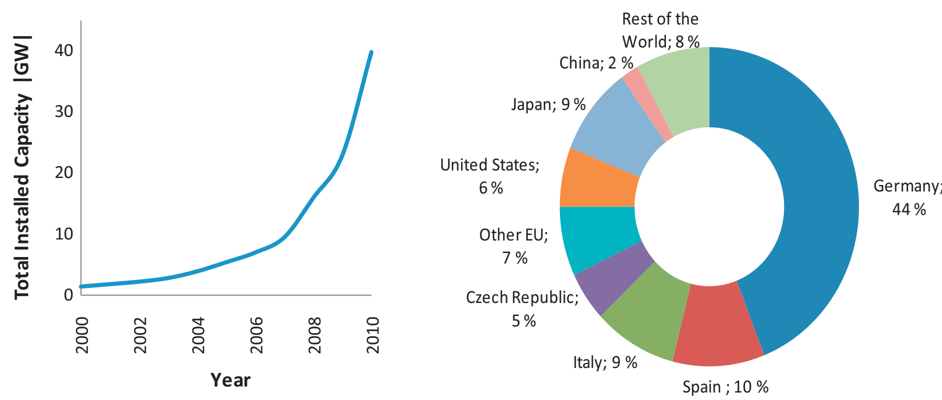
[3] With an assumption of CSP efficiency of 8 m^2/MWh/year, which is in the middle of the 4–12 m^2/MWh/year range offered by Muller-Steinhagen and Trieb [16].

[4] This, however, represents only about 0.8% of the total global installed power generation capacity of about 4600 GW in 2008.

Table 1
Annual technical potential of solar energy and energy demand (Mtoe).

Region	Minimum technical potential	Maximum technical potential	Primary energy demand (2008)	Electricity demand (2008)
North America	4322	176,951	2731	390
Latin America and Caribbean	2675	80,834	575	74
Western Europe	597	21,826	1822	266
Central & Eastern Europe	96	3678	114	14
Former Soviet Union	4752	206,681	1038	92
Middle East and North Africa	9839	264,113	744	70
Sub-Saharan Africa	8860	227,529	505	27
Pacific Asia	979	23,737	702	76
South Asia	907	31,975	750	61
Centrally Planned Asia	2746	98,744	2213	255
Pacific OECD	1719	54,040	870	140
Total	37,492	1,190,108	12,267	1446

Source: Johansson et al. [110]; IEA [111].
Note: The minimum and maximum reflect different assumptions regarding annual clear sky irradiance, annual average sky clearance, and available land area.



(a) Trend of global installed capacity **(b)** Country share in the global installation in 2010

Fig. 2. Total installed capacity of PV at the global level.
Source: REN21 [4].

in 2008. India had a cumulative installed PV capacity of 102 MW [21] and China had a cumulative capacity of 893 MW at the end of 2010.

Two types of PV systems exist in the markets: grid connected or centralized systems and off-grid or decentralized systems. The recent trend is strong growth in centralized PV development with installations that are over 200 kW, operating as centralized power plants. The leading markets for these applications include Germany, Italy, Spain and the United States. After exhibiting poor growth for a number of years, annual installations in the Spanish market have grown from about 4.8 MW in 2000 to approximately 950 MW at the end of 2007 [22] before dropping to 17 MW in 2009 and bouncing back to around 370 MW in 2010 [23]. The off-grid applications (e.g., solar home systems) kicked off an earlier wave of PV commercialization in the 1970s, but in recent years, this market has been overtaken by grid-connected systems. While grid-connected systems dominate in the OECD countries, developing country markets, led by India and China, presently favor off-grid systems. This trend could be a reflection of their large rural populations, with developing countries adopting an approach to solar PV that emphasizes PV to fulfill basic demands for electricity that are unmet by the conventional grid.[5]

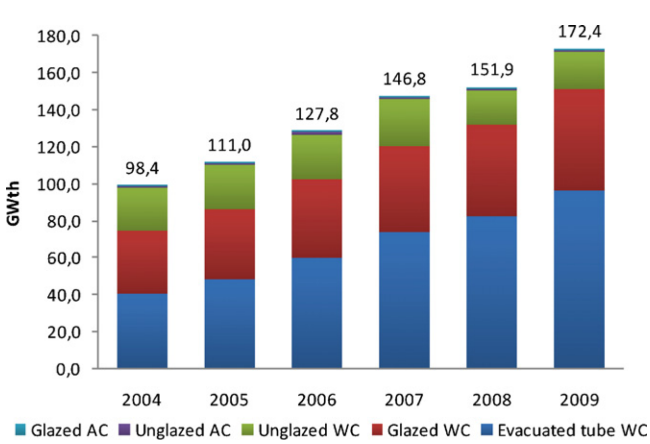


Fig. 3. Installed capacity of solar thermal systems.
Source: Weiss et al. [32]. WC is water collector and AC is air collector.

[5] By the early 1990s, off-grid applications accounted for about 20% of the market (based on power volume), while grid-connected systems accounted for about 11%. The rest of the market was comprised of remote stand-alone applications such as water pumping, communications, leisure, consumer products and so forth [24]. Between 1995 and 1998, for the first time, the market share of grid-connected systems eclipsed off-grid systems, when it grew to 23% of the PV installations [24]. Since that time, grid-connected PV capacity has dominated the market through sustained and dramatic growth rates. In both 2006 and 2007, this market attained 50% annual increases in cumulative installed capacity; in 2008 the growth further increased to 70% [4].

Table 2
Key data used in economic analysis.

Technology		Overnight construction cost (US$/kW)	Plant economic life (years)	Capacity factor (%)	Source
Solar PV	Min	2878	25	21	NEA/IEA
	Max	7381	25	20	NEA/IEA
Solar CSP	Min	4347	25	34	NEA/IEA
	Max	5800	20	26	Lazard
Wind	Min	1223	25	27	NEA/IEA
	Max	3716	25	23	NEA/IEA
Gas CC	Min	538	30	85	NEA/IEA
	Max	2611	30	85	NEA/IEA
Gas CT	Min	483	25	85	NEA/IEA [13]
	Max	1575	20	10	Lazard
Hydro	Min	757	80	34	NEA/IEA
	Max	3452	20	50	CPUC
IGCC w CSS[a]	Min	3569	40	85	NEA/IEA
	Max	6268	40	85	NEA/IEA
Supercritical[b]	Min	1958	40	85	NEA/IEA
	Max	2539	40	85	NEA/IEA
Nuclear	Min	3389	60	20	EIA
	Max	8375	20	90	Lazard

[a] IGCC with carbon capture and storage.
[b] Supercritical coal.

2.2.2. Concentrated solar power (CSP)

The CSP market first emerged in the early 1980s but lost pace in the absence of government support in the United States. However, a recent strong revival of this market is evident with 14.5 GW in various stages of development across 20 countries and 740 MW of added CSP capacity between 2007 and 2010 While many regions of the world, for instance, Southwestern United States, Spain, Algeria, Morocco, South Africa, Israel, India and China, provide suitable conditions for the deployment of CSP, market activity is mainly concentrated in Southwestern United States and Spain, both of which are supported with favorable policies, investment tax credits and feed-in tariffs [15]. Currently, several projects around the world are either under construction, in the planning stages, or undergoing feasibility studies[6] and the market is expected to keep growing at a significant pace [4].

2.2.3. Solar thermal for heating and cooling

The total area of installed solar collectors (i.e., non-electric solar thermal) amounted to 185 GW_{th} by early 2010 [5]. Of which China, Germany, Turkey and India accounted for 80.3%, 3.1%, 1.8% and 1.1%, respectively. The remaining 13.7% was accounted for other 40 plus countries including the USA, Mexico, India, Brazil, Thailand, South Korea, Israel, Cyprus, Ethiopia, Kenya, South Africa, Tunisia, and Zimbabwe. Three types of solar collectors (i.e., unglazed, glazed flat-plate and evacuated tube) are found in the market. By the end of 2009, of the total installed capacity of 172.4 GW_{th}, 32% was glazed flat-plate collectors; 56% was evacuated tube collectors; 11% was unglazed collectors; and the remaining 1% was glazed and unglazed air collectors [32]. The market for solar cooling systems remains small although it is growing fast. An estimated 11 systems were in operation worldwide by the end of 2009 [5]. The use of solar thermal non-electric technologies varies greatly in scale as well as type of technology preferred. For instance, the market in China, Taiwan, Japan and Europe is dominated by glazed flat-plate and evacuated tube water collectors. On the other hand, the North American market is dominated by unglazed water collectors employed for applications such as heating swimming pools.

3. The economics of solar energy

There is a wide variety of solar energy technologies and they compete in different energy markets, notably centralized power supply, grid-connected distributed power generation and off-grid or stand-alone applications. For instance, large-scale PV and CSP technologies compete with technologies seeking to serve the centralized grid. On the other hand, small-scale solar energy systems, which are part of distributed energy resources (DER)[7] systems compete with a number of other technologies (e.g., diesel generation sets, off-grid wind power, etc.). The traditional approach for comparing the cost of generating electricity from different technologies relies on the “levelized cost” method.[8] The levelized cost (LCOE) of a power plant is calculated as follows:

$$\text{LCOE} = \frac{\text{OC}}{\text{CF} \times 8760} \times \text{CRF} + \text{OMC} + \text{FC} \text{ with CRF} = \frac{r \times (1+r)^T}{(1+r)^T - 1}$$

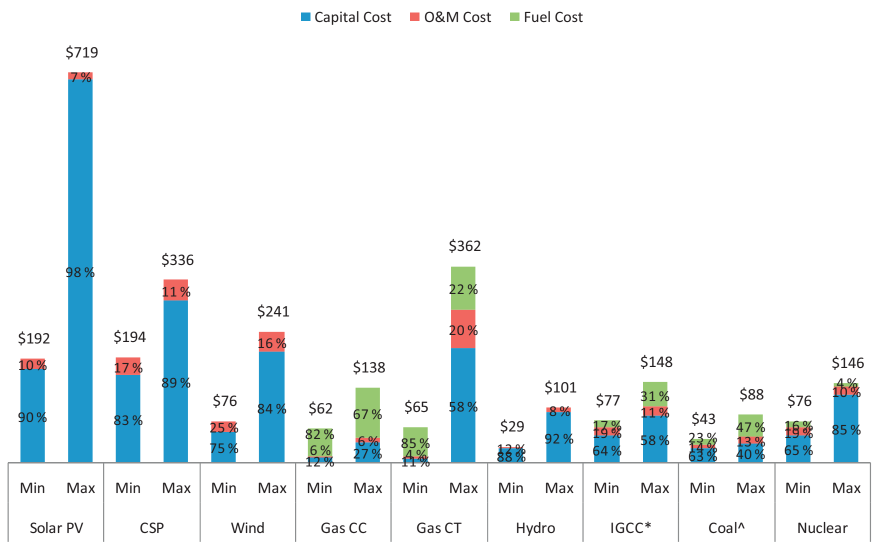
where OC is the overnight construction cost (or investment without accounting for interest payments during construction); OMC is the series of annualized operation and maintenance (O&M) costs; FC is the series of annualized fuel costs; CRF is the capital recovery factor; CF is the capacity factor; r is the discount rate and T is the economic life of the plant.

In this section, we discuss the economics of grid connected PV and CSP under various scenarios. One of the main challenges to the economic analysis of power generation technologies is the variation in cost data across technology type, size of plant, country and time. Since fuel costs are highly volatile and capital costs of solar technologies are changing every year, an economic analysis carried out in one year might be outdated the next year. Nevertheless,

[6] Examples of large solar thermal projects currently under construction or in the development stage around the world include: a 500 MW solar thermal plant in Spain; a 500 MW solar dish park in California; and 30 MW plants, one each in Egypt, India, Morocco and Mexico [25]. Solar Millennium AG, a German solar energy technology company, is working with its Chinese counterpart (Inner Mongolia Ruyi Industry Co. Ltd.) to build a multi-billion dollar CSP plant in northern China that would generate 1 GW by 2020 [26]. The Mediterranean Solar Plan, announced in July 2008, seeks to pursue the development of 20 GW of renewable energy in the Mediterranean region [4]. Some private companies have announced plans to develop 100 GW CSP capacity in the Sahara desert to supply electricity to Europe [27].

[7] DERs are essentially ‘small power generation and storage applications, usually located at or very near customer loads’ (Denny and Dismukes, 2002). Broadly, DERs include technologies and applications, which can be categorized into grid-connected applications, known as ‘distributed generation’ (DG) and a separate category known as stand-alone systems, which includes electric as well as non-electric applications [28,29].

[8] The levelized cost of electricity of a power plant represents the per unit value of total costs (i.e., capital, operation and maintenance, fuel) over the economic life of the power plant [30,31].



Note: * IGCC with carbon capture and storage. ^Supercritical coal.

Fig. 4. Levelized cost of electricity generation by technology (2008US$/MWh). *Note*: *IGCC with carbon capture and storage. ^Supercritical coal.

the analysis presented here could help illustrate the cost competitiveness of solar energy technologies with other technologies at present.

We have taken data from various sources including Lazard [6], NEA/IEA [33], NEA/IEA [30], EIA [34] and CPUC [35]. The data were available for different years, so we adjusted them using the GDP deflator and expressed them in 2008 prices for our analysis. Moreover, the existing calculations of LCOE for a technology vary across studies as they use different economic lives, capacity factors and discount rates. Some studies account for financial costs (e.g., taxes and subsidies) [6,35], while others include only economic costs [30,33]. Therefore, we have taken the maximum and minimum values of overnight construction costs for each technology considered here from the existing studies to reflect the variations in overnight construction costs, along with the corresponding O&M and fuel costs, and applied a uniform 10% discount rate and 2.5% fuel price and O&M costs escalation rate to cost data from all the studies. Since our focus is on economic analysis, taxes, subsidies or any types of capacity credits are excluded. See Table 2 for key data used in the economic analysis.

Fig. 4 presents the results of the levelized cost analysis. Although the costs of solar energy have come down considerably and continue to fall, the levelized costs of solar energy are still much higher compared to conventional technologies for electricity generation, with the exception of gas turbine.[9] For example, the minimum values of levelized cost for solar technologies (US$192/MWh for PV and US$194/MWh for CSP) are more than four times as high as the minimum values of the levelized cost of supercritical coal without carbon capture and storage (US$43/MWh). Among renewable energy technologies, wind and hydropower technologies are far more competitive with fossil fuel and nuclear power plants.[10]

The difference between the minimum and maximum values for the levelized costs of solar energy technologies (and also other energy technologies) are wide due mainly to large variations in overnight construction costs and to different capacity factors. For example, the overnight construction costs of grid connected solar PV system vary from US$2,878/kW to US$7,381/kW [30]. Similarly, the overnight construction costs of CSP vary from US$4,347/kW [30] to US$5,800/kW [6]. The capacity utilization factor of simple cycle gas turbine varies from 10% [6] to 85% [30]. Furthermore, very different economic lives are assumed for hydro, coal and nuclear plants.

It is also interesting to observe the contributions of various cost components (e.g., capital, O&M and fuel costs) to levelized cost. While capital cost accounts for more than 80% of the levelized cost for renewable energy technologies, it accounts for less than 60% in conventional fossil fuel technologies (e.g., coal, gas combined cycle). Fuel costs are the major components in most fossil fuel technologies.

Using the concept of experience or learning curves which plot cost as a function of cumulative production on a double-logarithmic scale, implying a constant relationship between percentage changes in cost and cumulative output,[11] existing studies (e.g., [37,40–45]), expect significant reductions in the capital costs of solar energy technologies (see Fig. 5a). The cost of solar PV has been declining rapidly in the past, compared not only to conventional technologies such as coal and nuclear, but also to renewable technology such as wind. The 2011 Special Report on Renewable Energy Carried out by Intergovernmental Panel on Climate Change Arvizu et al. [11] has also demonstrates reduction in costs of solar and wind power along with their cumulative installed

[9] In electricity systems, which face high natural gas price, the levelized cost of simple cycle gas turbine technologies is much higher as compared to that of other conventional technologies because the utilities dispatch this technology only when other technologies are not available, thereby resulting in a small capacity utilization factor. However, in some system where natural gas is the major source for electricity generation, a gas fired power plant could be also used to serve base load. In such cases, the capacity factor could be as high as 85% and its levelized cost would be lower.

[10] The costs estimated here are close to that compiled in Arvizu et al. [11].

[11] The concept of experience or learning curves was first used in the aircraft industry by T.P. Wright in 1936 with the idea that improvements in labor-hours needed to manufacture an airplane could be described mathematically. Since then, the analytical technique has been frequently used to assess trends in the cost competitiveness of technologies given the cumulative output, investment, or other measures of the application of the technology [36–39].

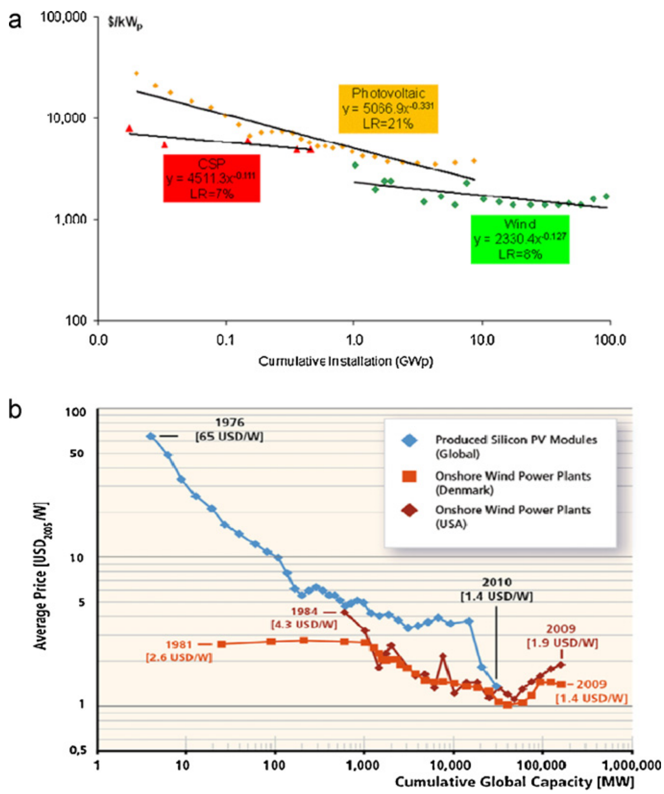


Fig. 5. Experience curves of renewable electric technologies.
Sources: Earth Policy Institute [112]; DOE [113]; Stoddard et al. [114]; Charls et al. [115]; Winter [116]; Arvizu et al. [11].

capacity (see Fig. 5b). The "learning rate"[12] of solar PV, CSP and wind are 21%, 7%, and 8%, respectively [46,47].[13]

Considering the declining trend of capital costs as discussed above, we analyzed the levelized costs of solar energy technologies when their capital costs drop by 5–25% from the present level. Fig. 6 shows how the levelized cost of solar thermal trough, solar thermal tower, photovoltaic thin-film and photovoltaic crystalline would decline if their capital cost requirements were to fall by up to 25% and how those costs would compare to the maximum levelized costs of traditional electricity generation plants. As illustrated in the figure, the minimum values of levelized cost of any solar technologies, including tower type CSP, which is currently the least costly solar technology, would be higher than the maximum values of levelized costs of conventional technologies for power generation (e.g., nuclear, coal IGCC, coal supercritical, hydro, gas CC) even if capital costs of solar energy technologies were reduced by 25%.

Since fossil fuels such as coal and gas produce negative externalities at the local level (e.g., local air pollution) as well at the global level (e.g., GHG emissions), whereas solar energy technologies do not, it would be unfair to compare solar energy technologies with fossil fuel technologies without accounting for those externalities. Hence, we further analyze the levelized costs of electricity generation technologies, developing a framework to capture some of those external costs. The framework accounts for the environmental damage costs of fossil fuels, particularly climate change damage costs. Damage costs of local air pollution are not included due to a lack of data. Since obtaining actual values of damage costs of emissions from different fossil fuel technologies is highly complex, we employed a sensitivity analysis by considering various values of damage costs ranging from US\$0/tCO_2 to US\$100/tCO_2. Fig. 7 plots the levelized costs of various technologies against the climate change damage costs. The figure demonstrates that the minimum values of levelized costs of solar energy technologies would be higher than the maximum values of the levelized costs of fossil fuel technologies even if the climate change damage costs of 100/tCO_2 are imputed to fossil fuel technologies. In other word, even if we assign a climate change damage cost of US\$100/tCO_2 to fossil fuel technologies, solar energy technologies would still presently be economically unattractive as compared to fossil fuel technologies.

The analysis above shows that climate change mitigation benefits would not be sufficient to make solar energy technologies economically attractive. However, solar energy technologies also provide additional benefits, which are not normally excluded from traditional economic analysis of projects. For example, as a distributed energy resource available nearby load centers, solar energy could reduce transmission and distribution (T&D) costs and also line losses. Solar technologies like PV carry very short gestation periods of development and, in this respect, can reduce the risk valuation of their investment [29]. They could enhance the reliability of electricity service when T&D congestion occurs at specific locations and during specific times. By optimizing the location of generating systems and their operation, distributed generation resources such as solar can ease constraints on local transmission and distribution systems [29,48]. They can also protect consumers from power outages. For example, voltage surges of a mere millisecond can cause 'brownouts,' causing potentially large losses to consumers whose operations require high quality power supply. They carry the potential to significantly reduce market uncertainty accompanying bulk power generation. Because of their modular nature and smaller scale (as opposed to bulk power generation), they could reduce the risk of over shooting demand, longer construction periods, and technological obsolescence [49]. Moreover, the peak generation time of PV systems often closely matches peak loads for a typical day so that investment in power generation, transmission, and distribution may be delayed or eliminated [29] However, developing a framework to quantify all these benefits is beyond the scope of this study.

4. Barriers to the development and deployment of solar energy technologies

The existing literature identifies a range of barriers that constrains the deployment of solar energy technologies for electricity generation and thermal purposes. These barriers can be classified as technical, economic, and institutional and are presented in Table 3.

Technical barriers vary across the type of technology. For example, in the case of PV, the main technical barriers include low conversion efficiencies of PV modules[14]; performance limitations of system components such as batteries and inverters; and inadequate supply of raw materials such as silicon. In the case of stand-alone PV systems, storage is an important concern, as is

[12] There are two important metrics devised to reflect the information contained in an experience curve and apply it for evaluative purposes, viz. "progress ratio" and "learning rate." The progress ratio is that proportion of original price, which results from a doubling of the cumulative volume. Thus, if the cost per unit reduces to 0.75 of the original price by doubling the cumulative output, then the progress ratio of such a technology is 75%. The learning rate for a particular technology is derived from the progress ratio by subtracting it from 1. Thus, if the progress ratio is 0.75, the corresponding learning rate for the technology is 0.25 or 25%.

[13] Note, however, that the application of this method to project actual experience with cost in established commercial-scale facilities is different than its application to cost changes as a technology moves from research phase to pilot investment to commercial use.

[14] Presently the highest efficiency for commercially available modules is 18% [50,51]. However, there is considerable scope for further efficiency improvements [52].

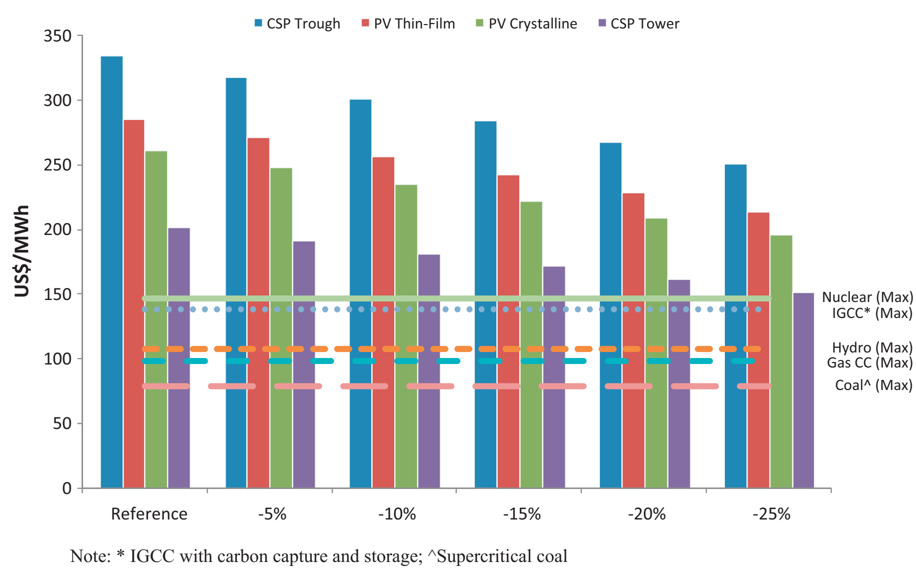


Fig. 6. Sensitivity of levelized costs of solar technologies to their capital cost reduction. *Note*: *IGCC with carbon capture and storage; ^Supercritical coal.

the shorter battery life compared to that of the module. Furthermore, safe disposal of batteries becomes difficult in the absence of a structured disposal/recycling process. With regard to solar thermal applications, there are two main technical barriers. They are limits to the heat carrying capacity of the heat transfer fluids and thermal losses from storage systems [53,54]. In addition, as seen in Table 3, there are constraints with regard to system design and integration as well as operating experience for system optimization. For example, lack of integration with typical building materials, designs, codes and standards make widespread application of solar space and water heating applications difficult. In the case of CSP, technologies such as the molten salt-in-tube receiver technology and the volumetric air receiver technology, both with energy storage systems, need more experience to be put forward for large-scale application [55]. Moreover, solar energy still has to operate and compete on the terms of an energy infrastructure designed around conventional energy technologies.

The economic barriers mainly pertain to initial system costs. Cost comparisons for solar energy technologies by suppliers and users are made against established conventional technologies with accumulated industry experience, economies of scale and uncounted externality costs. Solar energy technologies thus face an "uneven playing field," even as its energy security, social, environmental and health benefits are not internalized in cost calculations [56]. Financing is another critical barrier. Financial institutions consider solar energy technologies to have unusually high risks while assessing their creditworthiness. This is because solar energy projects have a shorter history, lengthy payback periods and small revenue stream [57,58]. This implies higher financial charges (e.g., interest rates) to solar energy projects.

Finally, both PV and solar thermal technologies face common institutional barriers. Broadly, these barriers arise from the novelty of these technologies. As such, they range from limited institutional capacities for workforce training to institutional mechanisms for planning and coordinating financial incentives and policies. Inadequate numbers of sufficiently trained people to prepare, install and maintain solar energy systems is a common barrier. Without a concerted effort to institutionalize the process of training, the diffusion of new technologies is often hampered. In India, for example, the country invested in the training of nuclear physicists and engineers since its independence, while similar requirements for renewable technologies were ignored [59]. In some instances, existing laws and regulations might constrain the deployment of solar energy. For example, PV systems have to overcome 'cumbersome and inappropriate' interconnection requirements such as insurance, metering and billing issues [60].

5. Policy instruments to support solar energy development

As illustrated earlier, many solar energy technologies are not yet cost-competitive with conventional energy commodities at either the wholesale or retail levels. Therefore, any significant deployment of solar energy will not be possible unless major policy incentives are introduced. A large number of governments have realized this and have supported solar energy development through a broad range of fiscal, regulatory, market and other instruments. A number of recent studies, such as [21,23,61] present in-depth analysis of various policy instruments designed to promote renewable energy, including solar, at the global level as well as for a particular country, such as India. In fact, the strong growth in solar energy markets, notably those for grid-connected solar PV and solar thermal water heating, has been driven by the sustained implementation of policy instruments in Europe, the United States and some

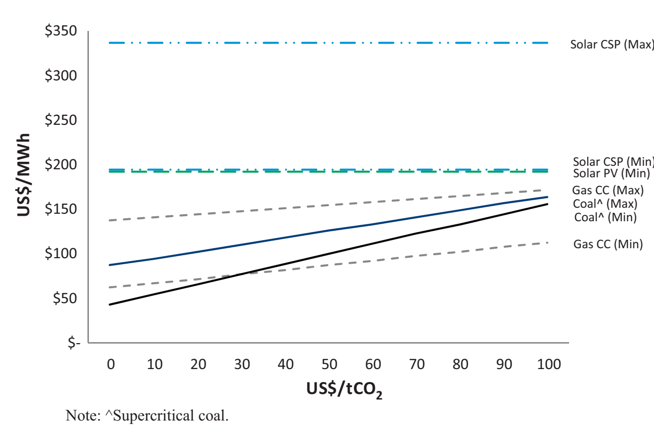


Fig. 7. Economic attractiveness of solar technologies when environmental damages of fossil fuel technologies are accounted. *Note*: ^Supercritical coal.

Table 3
Barriers to the development and deployment of solar energy technologies.

	PV	Solar thermal
Technical barriers	The efficiency constraint: 4–12% (for thin film) and under 22% (for crystalline) in the current market [66].	Heat carrying capacity of heat transfer fluids.
	Performance limitations of balance of system (BOS) components such as batteries, inverters and other power conditioning equipments [117–119].	Thermal losses and energy storage system issues with CSPs [53,54].
	Silicon supply: strong demand for PV in 2004 and 2005 outpaced the supply and partly stalled the growth of solar sector [120,121].	Supply orientation in the design of solar water heaters when product diversity is needed to match diverse consumer demand profiles.
	Cadmium and tellurium supply for certain thin film cells: these two components are by-products from respectively the zinc mining and copper processing and their availability depends on the evolution of these industries [66].	For solar water heating, lack of integration with typical building materials, existing appliances and infrastructure, designs, codes, and standards has hampered widespread application.
	Lack of adequate infrastructure to interconnect for hassle-free metering and billing [60].	In case of central receiver systems the promising technologies such as the molten salt-in-tube receiver technology and the volumetric air receiver technology, both with energy storage system needs more experience to be put for large-scale application [55].
Economic barriers	High initial cost and lack of easy and consistent financing options forms one of the biggest barriers primarily in developing countries [118].	High upfront cost coupled with lengthy payback periods and small revenue streams raises creditworthiness risks.
	Unusually high risks while assessed in creditworthiness determined by finance institutions because of their lack of experience with projects [57,58].	The financial viability of domestic water heating system is low.
	Cost of BOS is not declining proportional to the decline in module price [117].	Backup heater required in water heating systems to provide reliable heat adds to the cost.
	Bias against distributed technology platforms among conventional energy agencies and utilities [122].	Increasing cost of essential materials like copper make water heating and distribution costly.
		Limited rooftop area and lack of building integrated systems limit widespread application.
Institutional barriers	Lack of effective and appropriate laws such as Renewable Portfolio Standards (RPS) for utilities, to encourage wider adoption.	
	The limited ability to train adequate number of technicians to effectively work in a new solar energy infrastructure ([59]).	
	Limited understanding among key national and local institutions of basic system and finance factors.	
	The fragileness of solar development partnerships: many PV projects are based on development partnerships and with the early departure of a partner the revenue to complete, operate and maintain the system may falter [123].	
	Procedural problems such as the need to secure financing from multiple sources and approvals from several agencies (e.g., in India, MNRE, IREDA, the Planning Commission, and the Ministry of Agriculture and Rural Development) [124].	

developing countries. This section briefly presents key policy instruments that support solar energy for both electric and direct heating applications.

5.1. Policy instruments

A large number of policy instruments have been implemented to support solar PV and CSP. The key instruments we highlight here include feed-in-tariffs, investment tax credits, subsidies, favorable financing, mandatory access and purchase, renewable energy portfolio standards and public investment.

5.1.1. Feed-in-tariff

Feed-in-tariff (FIT) refers to a premium or tariff or payment to new and renewable energy technologies which are relatively expensive or may not be competitive with conventional technologies for electricity generation.[15] The tariff is based on the cost of electricity produced plus a reasonable profit for the producer. It aims to send a signal to potential investors to make long-term investments on new and innovative technologies and thus ultimately help drive down the costs of those technologies. This policy has been implemented in more than 75 jurisdictions around the world as of early 2010, including in Australia, EU countries, Brazil, Canada, China, Iran, Israel, the Republic of Korea, Singapore, South Africa,, Switzerland, the Canadian Province of Ontario and some states in the United States [4]. FIT has played a major role in boosting solar energy in countries like Germany and

[15] In different countries, feed-in-tariffs could also be referred to as Standard Offer Contracts, Renewable Tariffs, Advanced Renewable Tariffs, Renewable Energy Payments, etc. Irrespective of the term used to refer to it, the basic principle is to facilitate production of electricity through new and renewable energy technologies and 'feed' it into national energy systems, particularly to electricity grids.

Italy, which are currently leading the world in solar energy market growth. Mendonça and Jacobs [62] argue that FIT promotes the fastest expansion of renewable electric power at the lowest cost by spreading the costs among all electric utility customers. A study evaluating renewable energy policies in EU countries found that the FIT is the most effective policy instrument to promote solar, wind and biogas technologies [63].

FITs cover all types of solar energy technologies (e.g., small residential rooftop PV to large scale CSP plants). The tariffs, however, differ across countries or geographical locations, type and size of technology.

For example, German feed-in payments are technology-specific, such that each renewable energy technology type receives a payment based on its generation cost, plus a reasonable profit. The FIT is further subdivided by project size, with larger projects receiving a lower feed-in tariff rate in order to account for economies of scale, and by project type, with freestanding systems receiving a low FIT [64]. The current FITs for solar PV in Germany are 0.43 €/kWh for rooftop capacity less than 30 kW; 0.41 €/kWh for rooftop capacity between 30 kW and 100 kW; 0.39 €/kWh for rooftop capacity between 100 kW and 1 MW; 0.33 €/kWh for rooftop capacity greater than 1 MW; and 0.32 €/kWh for free-standing units [65]. Each tariff is eligible for a 20-year fixed-price payment for every kilowatt-hour of electricity generated. Germany's FiT assessment technique is currently based on a corridor mechanism [66]. This mechanism sets a PV capacity installation growth corridor which is dependent on the PV capacity installed the year before, and results in a decrease or an increase of the FiT rates according respectively to the percentage that the corridor path was exceeded or unmet. As PV capacity installations were superior than planned by government in 2010, the FiT rates were decreased by 13% on January 1st, 2011, thereby accounting for the decrease in PV costs.

The FIT is regarded as the key driver for growth of grid connected solar power, both CSP and grid connected PV. However, it still faces a number of challenges. Couture and Cory [67] identify several challenges to the FIT policy instrument. First, while the FIT provides incentives to investors by guaranteeing reasonable rates of return on investment, it does not help subsidize the high up-front costs. Second, the FITs on high cost technologies like solar put upward pressure on electricity rates in the near term to significantly scale up the deployment of such technologies. FIT policies guaranteeing grid interconnection, regardless of location on the grid, could increase transmission costs if projects are sited far from load centers or transmission or distribution lines. FIT policies designed to periodically adjust to account for changes in technology costs and market prices over time pose a challenge as changing payment levels too often can increase uncertainties to investor and overall market risk. In Germany, for example, there was political pressure to cap the policy or speed its rate of decline [68,69].

5.1.2. Investment tax credits

Different types of investment tax credits have been implemented in several jurisdictions around the world to support solar energy. In the United States, for example, the federal business energy investment tax credit is available for solar energy and fuel cells. For solar energy, the credit is equal to 30% of expenditures on equipment that uses solar energy to generate electricity, to heat or cool and on hybrid solar lighting systems. Besides the investment tax credits, the US Federal Government also provides an accelerated cost-recovery system through depreciation deductions: solar energy technologies are classified as five-year property. In addition, the federal Economic Stimulus Act of 2008, enacted in February 2008, and the American Recovery and Reinvestment Act of 2009, enacted in February 2009,[16] provide a 50% bonus depreciation to solar energy technologies implemented between 2008 and September 2010 and 100% bonus depreciation to solar energy technologies placed in service after September 2010. In the case of residential tax payers (i.e., non-business taxpayers), a taxpayer may claim a credit of 30% on qualified expenditures on solar energy equipments (e.g., labor costs for onsite preparation, assembly or original system installation). If the federal tax credit exceeds tax liability, the excess amount may be carried forward to the succeeding taxable year until 2016.

The 30% federal tax credits have provided significant leverage to solar energy development in the United Sates, where state governments have further supplemented federal tax incentives with their own programs. For example, the one megawatt CSP project (Sugarno project) installed by Arizona Public Service (APS) in 2006, and the 64 MW Nevada Solar One parabolic trough CSP installed in Boulder City, Nevada in 2007 have largely benefited from the federal tax credit scheme [70].

In Bangladesh, the primary driver of the PV market is microcredit finance that led to the substantial growth of privately owned Solar Home Systems (SHS) [71].

Despite their instrumental role in promoting solar energy, investment tax credits schemes are criticized for their impacts on government revenues. For example, the investment tax credits in the United States would cost approximately US $907 million over 10 years (Renewable Energy World, July 31, 2008). The tax rebate system in New Jersey would cost $500 million annually to reach the goal; to avoid such high costs, the State Government decided that only systems 10 kW and smaller would qualify for rebates, and systems larger than 10 kW would have to compete in a tradable solar renewable energy credit (SREC) market [72].

5.1.3. Subsidies

Subsidies are the primary instrument to support solar energy development in almost every country around the world. A subsidy could be investment grants or capacity payments, output or production based payments or soft loans (e.g., interest subsidies). In India, for example, the primary policy driver during the early years was capital subsidies funded either through donor and/or government funds. Currently, the production-based subsidy offered by the government has been supplemented by the prevalent rate structure for conventional electricity to offer a combined feed-in-tariff of about Rs. 15/kWh for solar PV and solar thermal projects commissioned after March 31st, 2011 for up to 25 years [73]. Remote village electrification programs receive even higher levels of subsidies. One such program that aims to establish a single light solar PV system in all non-electrified villages in India by 2012 has 90% of the system cost covered by the government subsidy. In the case of below poverty line (BPL) families, 100% of the system cost will be underwritten by the state governments [74].

The rebate program for solar PV in California under the California Solar Initiative (CSI) is another example of a subsidy scheme for solar energy. The goal of the $3.3 billion CSI program is to support the development of 3000 MW of PV in California by 2017 using rebates, also known as 'Buy-Down' and performance-based incentives (PBI). For systems 50 kW and smaller, the buy-down level is calculated based on expected system performance, taking tilt, location and orientation into account; the subsidy is referred to as Expected Performance-Based Buy-Down (EPBB). The better the system is projected to perform, the higher the rebate it receives.

[16] The American Recovery and Reinvestment Act of 2009 also allows taxpayers to receive a grant from the U.S. Treasury Department instead of taking the business ITC for new installations. The grant is equal to 30% of the basis of the property for solar energy. In the case of fuel cells, the grant is capped at $1500 per 0.5 kW in capacity.

The level of Buy-Down starts at $2.80 for the private sector and for the public sector and non-profit organizations, which cannot take advantage of the federal tax credit. The rate declines when certain blocks of capacity are reached Systems over 50 kW are eligible for a five-year PBI which declines in steps similar to the EPBBs. Step 2 includes incentives of $0.39/kWh for private sector organizations, and $0.50/kWh for non-profit and public sector organizations. Preliminary results indicate that the ambitious target set under the CSI can be reached [75] with 506 MW already installed by April 2011 and another 403 MW pending. Progresses have been most impressive in the residential sector while progresses are slower for the non-residential sector. Earlier experiences with the program indicated that it would have some trouble achieving its targets without programmatic adjustments [76], however, increasing rate of new solar installation since 2008 put the program back on track. Although the CSI declines were built into the program to encourage PV costs to decline, it is difficult to match incentive schedules to experience curves [77], and the CSI incentives declined far faster than the 7% annually projected by the program [78]. As a result, it remains to be seen whether incentive levels will be too low to sustain market growth in the future, and whether the market will be able to force installation costs low enough to supply attractive systems to customers [79].

The Spanish government launched a program to provide grants of between €240.40/m^2 and €310.35/m^2 in 2000 to solar thermal technologies. In India, solar hot water systems, solar cooking systems and concentrating solar cookers receive capital subsidies of, respectively, Rs. 1500, Rs. 1250 and Rs. 2000 per square meter. The primary reliance on capital subsidies has come under criticism because it incentivized capacity and not necessarily production [80]. In response to these changes, government policy for PV in India has recently been revised.

5.1.4. Renewable energy portfolio (RPS)

Many countries, particularly developed countries, have set penetration targets for renewable energy in total electricity supply mix at the national or state/provincial levels. To meet the targets, electricity suppliers (e.g., utilities, distributors) are required to have certain percentage of their electricity supply coming from renewable energy sources. These standards are commonly known as renewable energy portfolio standards (RPS) or Tradable Green Certificate (TGC) schemes in Europe. The standards create a trading regime where utilities with no or low renewable electricity content in their overall supply portfolio buy from those with high renewable electricity content. In the United States, 31 out of 50 States have introduces RPS. The standards range from 10% to 40% (Hawaii by 2030). New Jersey became the first state to create an RPS with specified standards for solar energy. The New Jersey RPS required that 6.8% of the electricity sold in the state be renewable by 2008, of which 0.16% was to come from PV. This created a stand-alone market for solar renewable energy credits (SRECs), whose market price was capped through the use of an "alternative compliance payment" (ACP) of $300/MWh. In 2010, New Jersey revised its RPS to require 20.38% of its electricity to come from renewables by 2021. In addition, 2,518 GWh from in-state solar electric facilities must be generated in 2021 and 5316 GWh in 2026 [81]. Similarly, Nevada's RPS mandates that 20% of state electricity come from renewable resource by 2015. Of that, 5% must come from solar power [82]. RPS contributed substantially to the realization of large scale CSP plants, such as the 500 MW CSP project in the Imperial Valley in California.

5.1.5. Financing facilitation

In India, the Shell Foundation worked with two leading banks in India, *viz.* Canara Bank and Syndicate Bank, to develop renewable energy financing portfolios. This project helped the banks put in place an interest rate subsidy, marketing support and vendor qualification process. Using the wide network of their branches, the interest subsidies were made available in over 2000 branch offices in the two states of Kerala and Karnataka. Within two and half years, the programs had financed nearly 16,000 solar home systems, and the subsidies were gradually being phased out. Whereas in 2003 all sales of PV home systems were on a cash and carry basis, by 2006, 50% of sales were financed [83].

In Bangladesh, the Rural Electrification and Renewable Energy Development Project established microcredit financed facilities that resulted in the installation of over 970,000 solar–home systems (SHS) between 2003 and May 2011. Having exceeded its expectations, the program now has a target of 1 million SHS systems by 2012 [84]. This model has been built on the microcredit banking system pioneered by Grameen Bank and now adopted by numerous organizations [71].

The Spanish government launched a program of low-interest loans for solar thermal applications (7-year loans with interest rates at 2–3.5% below commercial rates) in 2003 [85].

5.1.6. Public investment

One of the main drivers of solar energy development in developing countries is public investment. Many developing countries host a number of government and/or donor-funded projects to support solar energy under their rural electrification programs. The rapid development of the PV industry and market in China is mainly due to government support, implemented through a number of rural electrification programs. Programs for rural electrification were the major driving force for solar PV market expansion in China in the late 1990s and early 2000s. Most of the PV projects were government sponsored with international aid or within the framework of government programs at the national or local levels. The major programs supporting PV programs are Brightness Program Pilot Project, Township Electrification Programs, and China Renewable Energy Development Project. The Brightness Program Pilot Project, launched in 2000, plans to provide electricity to 23 million people in remote areas by 2010, using 2300 MW of wind, solar PV, wind/PV hybrid and wind/PV/diesel hybrid systems. Inner Mongolia, Gansu and Tibet were selected as pilot provinces, and a RMB 40 million grant was allocated for the project [86]. The Township Electrification Programs, launched in 2002, installed 268 small hydro stations and 721 PV, PV/wind hybrid systems by 2005 [87]. The overall investment was RMB 2.7 billion, and 15.3 MWp of PV systems were installed during the life of the program. The China Renewable Energy Development Project (REDP), also launched in 2002 and supported by a GEF grant, provided a direct subsidy of US$1.5 per Wp to PV companies to help them market, sell and maintain 10 MWp of PV systems in Qinghai, Gansu, Inner Mongolia, Xinjiang, Tibet and Sichuan.

Developing countries initiated programs with the help of bilateral and multilateral donor agencies are mainly facilitating solar energy development in developing countries. For example, the World Bank has launched a rural power project in the Philippines, aimed at the installation of 135,000 solar systems; totaling 9 MW installed capacity. In addition, the International Finance Corporation finished a 1 MW grid-tied PV with hydro hybrid project in the Philippines [88].

In the United States, the federal Energy Policy Act of 2005 established Clean Energy Renewable Bonds (CREBs) as a financing mechanism for public sector renewable energy projects. This legislation originally allocated $800 million of tax credit bonds to be issued between January 1, 2006, and December 31, 2007. The Energy Improvement and Extension Act of 2008 allocated $800 million for new CREBs. The American Recovery and Reinvestment Act of 2009 has allocated an additional $1.6 billion for new CREBs, thereby increasing the size of new CREB allocation to $2.4 billion.

In October 2009, the Department of Treasury announced the allocation of $2.2 billion in new CREBs for 805 projects across the country. CREBs may be issued by electric cooperatives, government entities (states, cities, counties, territories, Indian tribal governments or any political subdivision thereof) and by certain lenders. Moreover, the U.S. Department of Agriculture established the Rural Energy for America Program (REAP), which provides grants and loan guarantees for investments in renewable energy systems, energy efficiency improvements and renewable energy feasibility studies. A funding of $255 million has been allocated under this program for the 2009–2012 period.

5.1.7. Net metering

Net metering is the system where households and commercial establishments are allowed to sell excess electricity they generate from their solar systems to the grid. It has been implemented in Australia, Canada, United States and some European countries including Denmark, Italy and Spain. In the US, for example, most net metering programs are limited to renewable energy facilities up to 10 kW. In California it could reach up to 1 MW. In Canada, it goes up to 100 kW in Prince Edward Island and 500 kW in Ontario. Most programs only permit banking of electricity up to the customer's total annual consumption, and no payment is offered for any electricity generated above this amount. They receive the same price for generation: the retail tariff.

5.1.8. Government mandates and regulatory provisions

In many countries, governments have introduced laws mandating transmission companies and electricity utilities to provide transmission or purchase electricity generated from renewable energy technologies, including solar. In January 2006, China, for example, issued the Renewable Energy Law, mandating utility companies to purchase "in full amounts" renewable energy generated electricity within their domains at a price that includes production cost plus a reasonable profit. The extra cost incurred by the utility will be shared throughout the overall power grid [89]. Similarly, in Germany, all renewable energy generators are guaranteed to have priority access to the grid. Electric utilities are mandated to purchase 100% of a grid-connected PV system's output, regardless of whether the system is customer-sited or not.

Government regulations mandating installation of solar thermal systems is the main policy driver for the development of solar thermal applications in many countries (e.g., Spain, Israel). Israel has had a solar water heating obligation for new construction in place since the 1980s, but it did not spread to other countries immediately. In the late 1990s, the City of Berlin proposed to create a similar solar water heating mandate, but was unsuccessful in its attempt. The Spanish city of Barcelona, however, adapted the proposed Berlin mandate, and passed an ordinance in July, 1999, requiring that all new construction or major renovation projects be built with solar water heating [90].[17] The original ordinance, which targeted only certain building subsets, such as residential buildings, hotels, and gymnasiums, required that at least 60% of the hot water load be supplied by solar energy. The "Barcelona model" was adopted by 11 other Spanish cities by 2004 [93], including Madrid, and in 2006, Spain passed a national law requiring solar water heating on new construction and major renovations [94].

In China, the Renewable Energy Law requires the government to formulate policies that guide the integration of solar water heaters (SWH) and buildings; real estate developers to provide provisions for solar energy utilization; and residents in existing buildings to install qualified solar energy systems if it does not affect building quality and safety [89]. In regions with high solar radiation, hot water intensive public buildings (such as schools and hospitals) and commercial buildings (such as hotels and restaurants) should be gradually mandated for SWH installation. New buildings should reserve spaces for future SWH installation and piping [95]. At provincial and local levels, the governments have issued various policies for SWH promotion; for instance, Jiangsu, Gansu and Shenzhen require buildings of less than 12 floors to be equipped with solar water heaters [96,97].

5.2. Policy mix

The rapid growth of the grid-connected PV and CSP market is largely attributed to a policy suite that guarantees attractive returns on investment along with the technical and regulatory requirements such as grid connectivity and power purchase commitments required to incentivize investments. While FITs played an instrumental role in Germany and Italy, a mix of policy portfolios that includes federal tax credits, subsidies and rebates, RPS, net metering and renewable energy certificates (REC) facilitated solar energy market growth in the United States. Although some policy instruments have leading roles in promoting solar energy in some countries, a mix of policy instruments, instead of a single policy, would be more effective. For example, when the initial 354 MW of parabolic trough CSP was constructed in California, it benefited from the combination of federal tax credits, favorable utility power purchase agreements, and property tax exemptions from the State. Although property tax exemptions may not be a significant incentive for residential PV systems, property taxes can amount to millions of dollars for large-scale, ground-mounted solar thermal electric projects.[18]

The capital subsidy was the predominant policy instrument early on in India, but a mix of policy instruments, such as, subsidies, fiscal incentives, preferential tariffs, market mechanisms and legislation, were encouraged later for the deployment of solar energy [74]. For instance, in 2004–05, the subsidy for the solar photovoltaic program varied between 50% and as high as 90% for the 'special category states and islands.' Similarly, the subsidy for solar photovoltaic water pumping was Rs. 100/Wp and as much as Rs. 135/W in the special category states [59]. The growing role of private finance has reduced the role of fiscal policy drivers in the overall financing mix for solar power, and capital subsidies have been ratcheted down substantially, except in exceptional cases such as 'remote villages and hamlets.' India now relies on a mix of mechanisms including various tax and generation-based incentives, renewable purchase obligations, capital subsidies and accelerated depreciation. Yet, the accumulation of incentive programs and the failure to coordinate them is thought to hinder the development of renewable energy resources in India as it results in unnecessary delays and conflicts [61].

New Jersey also was successful in developing a policy mix that combined a broad range of federal and state incentives to drive rapid market growth: a policy portfolio consisting of RPS, federal

[17] The ordinance led into an increase in solar thermal capacity from 1560 m^2 in 2000 to 31,050 m^2, or 27 MW_{th}, by 2005 in Barcelona [91]. The rapid diffusion of this model to other municipalities and regions caused the Spanish solar thermal market to grow by 150 MW_{th} in 2007 [92]. In 2008, a national ordinance came into effect, which is expected to add between 1050 and 1750 MW_{th} of capacity by 2010 [94]. In addition, the Barcelona model has been adopted by four other European countries, and the European Commission (2008) has included renewable energy building obligations in its latest proposal for a Renewable Directive to the European Union.

[18] In 1990, when the outgoing California Governor Deukmejian vetoed the property tax exemption during his last two hours in office, it led to the bankruptcy of the solar thermal developer, Luz Limited International, and brought a halt to solar thermal development in the US [98].

tax credits, grants, drove the rapid growth of the PV market in New Jersey.

The combination of excellent solar resources, the 30% federal tax credit, and RPS policies in the Southwest United States has resulted in a rebirth of solar thermal electric generation. In two of the three states exploring solar thermal electric, the existence of a solar- or distributed generation-specific RPS tier has also played a role in successful project development.

In the Philippines, the portfolio of policy instruments includes duty-free importation of equipment, tax credits on domestic capital equipment and services, special realty tax rates, income tax holidays, net operating loss carry-over, accelerated depreciation and exemption from the universal charge and wheeling charges [99].

5.3. Policy challenges

The policy landscape for solar energy is complex with a broad range of policy instruments driving market growth. The rapid market growth of solar energy in Germany and Spain could be attributed to the feed-in-tariff systems that guarantee attractive returns on investment along with the regulatory requirements mandating 100% grid access and power purchase. On the other hand, federal and state incentives, along with regulatory mechanisms such as RPS, get credit for the rapid deployment of solar energy in the United States. In both markets, the policy landscape is in a transitional phase. In Germany, the FIT level is being reduced, whereas in the United States, upfront incentives are being shifted toward performance-based incentives. It is, however, uncertain if the transition will produce expected results. The decrease in the FIT, the primary basis for investors' confidence, could drive investors away from solar energy markets.

Sensitivity to policy costs is more significant in developing country markets such as India, China, Brazil, Philippines and Bangladesh. Thus, a common approach toward renewable energy technologies, seen in developing countries, is to "rationalize development and deployment strategy" [74] of renewable energy technologies. For instance, India planned in its eleventh Five-Year plan (2007–2012) to install 15,000 MW of grid-connected renewable energy and it was widely believed that this market expansion would be driven by wind, micro-hydro and biomass, as the plan recognized that solar PV would be an option only if the prices come down to levels comparable to micro-hydro. More recently, the National Solar Mission promoting solar power in India has been launched. The first phase (2009–2013) targets to increase the utility grid power from solar sources, including CSP, by over a 1 GW [61]. By 2022, 20 GW of solar capacity shall have been added in India. The approach to the renewable energy mix in China, Philippines and Bangladesh represents similar priorities of rationalizing the policy costs. In Brazil, as in other developing countries, the minimal policy cost is ensured via technology-specific and reserve energy auctions [61] as the cheapest renewable energy projects are implemented first.

Solar PV is recognized as serving a niche market that is very important in developing countries—electrification of rural and peri-urban areas that do not yet have access to the electric grid. There are vigorous efforts to expand the market for Solar Home Systems (SHS) as a means toward rural electrification. However, rural and peri-urban areas are characterized by low income households that may not be able to afford solar energy technologies unless they are substantially subsidized. Until now, the approach is to provide subsidies either via government funds or through international donors. However, a subsidy is a short-term support, not a long-term solution.

CSP and solar water heating are comparatively cheaper than solar PVs. These could be cost competitive with conventional fuels if existing subsidies to the latter are reduced or removed. However, fossil fuel subsidies are politically sensitive in many countries and their removal might take time. Thus far, CSP has not found much success in a developing country context. Unlike Solar PV, CSP is limited to utility scale applications and as such is often out of consideration in the traditional utility generation market due to current prices. Thus, developing country governments have adopted a cautious policy approach to this market, focusing more on pilot scale projects, as with grid-connected solar PV. Through its National Solar Mission, India is the first developing country to take a step toward the installation of CSP capacity.

Unlike in electric applications, solar heating applications enjoy limited policy support as instruments like FITs and RPS are not applicable for heating applications. Moreover, it is more difficult to measure and verify solar water heating performance, and so performance-based incentives are harder to enact.

6. Solar energy development under the climate change regime

Climate change mitigation policies and activities help support renewable energy development, including solar energy. Various incentives and mandates designed to trigger GHG mitigation have helped promote solar energy in industrialized countries. In the case of developing countries, the clean development mechanism (CDM) under the Kyoto Protocol is the main vehicle to promote solar energy under the climate change regime. The CDM allows industrialized countries to purchase GHG reductions achieved from projects in developing countries, where reducing GHG emissions is normally cheaper than in industrialized countries.

As of July 2011, there are 6416 projects already registered or in the process of registration under the CDM. Of these, 109 projects are solar energy projects with annual emission reduction of 3,570,000 tons of CO_2. Out of these 109 projects, 89 are located in China, South Korea and India. However, the solar energy projects account for a very small fraction (<1%) of total emission reductions from the total CDM projects already registered or placed in registration process [100].

There are two main reasons which explain the small share of solar energy projects in the global CDM markets: cost and economy of scale. Solar energy technologies are not yet economically competitive with other CDM candidates such as wind power, small hydro, landfill gas, biomass cogeneration etc. The high upfront capital investment cannot be recovered even if the revenue generated from sales of emission mitigation is included besides revenue from electricity sales. Second, solar energy projects come in smaller size; the transaction costs incurred in various steps during the CDM process (e.g., validation and registration of projects and monitoring, verification and certification of emission reductions) are often prohibitive for solar energy projects which are already less attractive compared to their competitors.

There could be a number of ways to address the barriers to CDM registration of solar energy projects. First, full accounting of social benefits, such as environmental benefits, enhanced energy security and low carbon economic development realized through solar energy projects. One approach considered by a number of countries is that solar energy technologies receive some premium for their social and environmental benefits. Second, reducing the transaction costs of diffused, small-scale solar CDM projects by bundling them into a single larger portfolio project. The 'Programmatic CDM' schemes would be instrumental in this direction.[19] Third, further simplification of CDM registration process by avoiding additionality

[19] Programmatic CDM refers to an action that implements any policy/measure or stated goal (i.e. incentive schemes), which leads to GHG reductions or removal. This

screening for solar energy technologies as they meet the additionality criterion by default. Fourth, capacity building in developing countries through the enhancement of the technical and managerial capacity that is essential for market participants, including businesses and other stakeholders, to become active in the promotion of solar projects qualifying for CDM investment [102].

7. Future prospects for solar energy

Solar energy is expected to play a crucial role in meeting future energy demand through clean energy resources. Existing studies expect the long-term growth (e.g., until 2050) of solar energy vary widely based on a large number of assumptions. For example, Arvizu et al. [11] argues that expansion of solar energy depends on global climate change mitigation scenarios. In the baseline scenarios (i.e., in the absence of climate change mitigation policies), the deployment of solar energy in 2050 would vary from 1 to 12 EJ/yr. In the most ambitious scenario for climate change mitigation, where CO_2 concentrations remain below 440 ppm by 2100, the contribution of solar energy to primary energy supply could reach 39 EJ/yr by 2050.

EPIA/Greenpeace [66] produces the most ambitious forecasts for future PV installation. The study argues that if existing market supports are continued and additional market support mechanisms are provided, a dramatic growth of solar PV would be possible, which will lead to worldwide PV installed capacity rising from around 40 GW in 2010 to 1845 GW by 2030. The capacity would reach over 1000 GW in 2030 even with a lower level of political commitment.

A study jointly prepared by Greenpeace International and the European Renewable Energy Council [104] projects that installed global PV capacity would expand to 1330 GW by 2040 and 2033 GW by 2050. A study by the International Energy Agency [103] estimates solar power development potential under two scenarios that are differentiated on the basis of global CO_2 emission reduction targets. In the first scenario, where global CO_2 emissions in 2050 are restricted at 2005 level, global solar PV capacity is estimated to increase from 11 GW in 2009 to 600 GW by 2050. In the second scenario, where global CO_2 emissions are reduced by 50% from 2005 levels by 2050, installed capacity of solar PV would exceed 1100 GW in 2050.

Like solar PV, projections are available for CSP technology. A joint study by Greenpeace, the European Solar Thermal Power Industry (ESTIA) and the International Energy Agency projects that global CSP capacity would expand by one hundred-fold to 37 GW by 2025 and then skyrocket to 600 GW by 2040 [105]. Teske et al. [104] project that Global CSP capacity could reach 29 GW, 137 GW and 405 GW in 2020, 2030 and 2050, respectively. [103] projects that CSP capacity could reach 380 GW to 630 GW, depending on global targets for GHG mitigation.[20]

In the case of solar thermal energy, the global market could expand by tenfold to approximately 60 million tons of oil equivalent (Mtoe) by 2030 [106]. A more optimistic scenario from the European Renewable Energy Council [10] projects that solar thermal will grow to over 60 Mtoe by 2020, and that the market will continue to expand to 244 Mtoe by 2030 and to 480 Mtoe, or approximately 4% of total global energy demand, by 2040.

It would be also relevant to envisage the contribution of solar energy to the global energy supply mix. According to EREC [107], renewable energy is expected to supply nearly 50% of total global energy demand by 2040. Solar energy alone is projected to meet approximately 11% of total final energy consumption, with PV supplying 6%, solar heating and cooling supplying 4% and CSP supplying 1% of the total. Shell [108] shows that if actions begin to address the challenges posed by energy security and environmental pollution, sources of energy other than fossil fuels account for over 60% of global electricity consumption, of which one third comes from solar energy. In terms of global primary energy mix, solar energy could occupy up to 11% by 2050.

8. Conclusions

Solar energy constitutes the most abundant renewable energy resource available and, in most regions of the world, its technically available potential is far in excess of the current total primary energy supply in those regions. Solar energy technologies could help address energy access to rural and remote communities, energy security and climate change mitigation are a key tool to lower worldwide carbon emissions.

The market for technologies to harness solar energy has seen dramatic expansion over the past decade—in particular the expansion of the market for grid-connected distributed PV systems and solar hot water systems have been remarkable. Notably, centralized utility scale PV applications have grown strongly in the recent years; off-grid applications are now dominant only in developing markets. Moreover, the market for larger solar thermal technologies that first emerged in the early 1980s is now gathering momentum with a number of new installations as well as projects in the planning stages.

While the costs of solar energy technologies have exhibited rapid declines in the recent past and the potential for significant declines in the near future, the minimum values of levelized cost of any solar technologies, including tower type CSP, which is currently the least costly solar technology, would be higher than the maximum values of levelized costs of conventional technologies for power generation (e.g., nuclear, coal IGCC, coal supercritical, hydro, gas CC) even if capital costs of solar energy technologies were reduced by 25%. Currently, this is the primary barrier to the large-scale deployment of solar energy technologies. Moreover, the scaling-up of solar energy technologies is also constrained by financial, technical and institutional barriers.

Various fiscal and regulatory instruments have been used to encourage solar energy. These instruments include tax incentives, preferential interest rates, direct incentives, loan programs, construction mandates, renewable portfolio standards, voluntary green power programs, net metering, interconnection standards and demonstration projects. However, the level of incentives provided through these instruments does not seem to be adequate to substantially increase the penetration of solar energy in the global energy supply mix.

Carbon finance mechanisms, particularly the CDM, can potentially support expansion of the solar energy market, but this has not materialized yet. This situation can be redressed by policy incentives such as a premium for solar-based CERs; reducing transaction costs by bundling of diffused small-scale solar CDM projects; and initiating programmatic CDM by local governments or private initiative. Note that the price of carbon credits required to make solar energy technologies economically competitive with other technologies to reduce GHG emissions would be high.

The current growth of solar energy is mainly driven by policy supports. Continuation of existing supports and introduction of new supports would be necessary for several decades to enhance the further deployment of solar energy in both developed and developing countries.

allows bundling of several similar CDM project activities to implement them under a single program [101].

[20] The lower range represents to the scenario of limiting global CO_2 emissions in 2050 at 2005 level, whereas the upper range refers to the scenario to reduce global CO_2 emissions in 2050 by 50% from 2005 levels.

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